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Parabolic trough solar receivers characterization using specific test bench for transmittance, absorptance and heat loss simultaneous measurement

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ABSTRACT

Parabolic trough is the most extended solar thermoelectric technology. Solar radiation is converted into heat and transferred to the heat transfer fluid in the solar receiver tubes. The thermal energy obtained feeds a conventional Rankine power cycle. The performance of the receiver tube can be broken down into three single components: the optical transmittance of the outer glass envelope or capability in transmitting the radiant energy; the optical absorptance of the metal tube or capability to absorb the radiation; and heat losses of the tube or capability to retain the heat which depends of inner tube coating emissivity and the vacuum between both tubes. In this paper a novel test bench implementing both thermal and optical measurement systems is described and compared with other systems referred in the literature. The results obtained from the evaluation of three different solar receivers with different diameters are presented. Optical measurements of transmittance and absorptance parameters are carried out in the wavelength range of 300–2500 nm. Optical evaluation of trough receivers at operating temperatures up to 450 °C is feasible. The receivers can be heated using a high intensity electric current flowing through the internal tube. Uniform Joule heating results a reliable heat losses measurement method at temperatures up to 650 °C.

1. Introduction

Solar thermoelectric technology has emerged as an alternative to conventional energy sources. Major players in this sector have made big efforts in research and development to achieve performance increase and cost reduction.

Parabolic trough represents the most common STE technology. Solar radiation concentrated by mirrors is converted into heat in receiver tubes. According to Fernandez-García et al. (2010) and Price (2003), receiver tube represents a key component and its performance influences decisively the overall plant efficiency.

Receiver tubes require maximum solar energy absorption and minimum heat losses. Receivers are configured with two coaxial tubes with vacuum in the inter-annular space. Vacuum reduces conductive and convective thermal losses and thus increases the efficiency of the energy generation process. The inner metal tube or absorber tube uses a high absorption and low emissivity coating (Kennedy, 2002) to reduce losses caused by thermal radiation in the far infrared. Coatings have an essential role in the performance of the receiver. The outer tube or glass envelope is covered with an antireflective coating to increase the amount of energy transmitted inwards.

In order to characterize the thermal and optical efficiency of receivers, appropriate systems are required. Some portable devices to evaluate operating receivers in the solar field exist. For the optical properties, portable spectrophotometers (Espinosa and Martinez, 2014; Navarro-Hermoso and Martinez, 2015) allow measuring the transmittance and reflectance (and thus the absorptance) of receivers at some wavelengths along the solar spectrum. Regarding the thermal performance, Navarro-Hermoso et al. (2016) presents a non-contact and simultaneous measurement of the inner and outer tubes temperatures estimating the thermal performance of operating tubes.

Abbreviations: STE, solar thermoelectric; R&D, research and development; PT, parabolic trough; IR, infrared; ASTM, American Society for Testing Materials; SRC, spectral reflectance curve; STC, spectral transmittance curve; SD, standard deviation; OH, hydroxyl group.

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Non-portable systems to carry out accurate and non-destructive measurement on receiver tubes exist. Testing facilities for thermal characterization have been presented in the literature (Lei et al., 2013; Gong et al., 2010; Lüpfert et al., 2008; Sanchez et al., 2010). They use electrical heating elements fixed to the absorber tube to obtain the heat losses. These systems do not characterize the optical efficiency.

Some techniques propose measurement systems based on energy balances. Both outdoors test systems using solar radiation (Pernpeintner et al., 2009; Lüpfert et al., 2008; Kutscher et al., 2014) and laboratory solar simulation systems (Pernpeintner et al., 2009, 2015; Okuhara et al., 2015) are presented in the literature. These systems evaluate an overall heat collection efficiency which includes the optical and thermal efficiency. In case that heat losses are known, the optical efficiency can be calculated. Optical properties, transmittance and absorptance, cannot be reported separately. The results obtained are strongly dependent on the incident irradiance measurements.

In this paper a novel test bench system to characterize both thermal and optical properties of PT receiver tubes is presented. Optical measurements of transmittance and reflectance parameters in the wavelength range of 300–2500 nm and can be taken at any point of the tube. The optical system of the test bench has similarities to the one presented by Sanchez et al. (2010) and Mateu et al. (2011), including relevant improvements. For example, the optical design of the test bench presented makes possible measurements on receivers of different diameters, which was not possible previously; also, the temperature range wherein optical measurements can be performed with precision is expanded up to 450 °C by minimizing the effect of the IR radiation from the heated tube using a reduced acceptance angle.

Another new feature is that the heat losses measurement system is integrated in the same test bench. This system is based on a high intensity electric current flowing through the absorber tube similar to the one presented by Dreyer et al. (2010). Uniform Joule heating provides a fast and reliable heat losses measurement method at temperatures up to 650 °C. Thus, the presented test bench can report separately spectral transmittance, spectral absorptance and heat losses values.

This paper presents the results of the optical and thermal characterization of three different receivers. For the first time to our knowledge, optical behavior of a tube at temperatures up to 450 °C is reported. A discussion of the presented measurement method and measured parameters is done.

2. Solar receiver test bench description

A test bench for the optical and thermal characterization of PT receiver tubes has been designed and built. The test bench presented is shown in Fig. 1.

Fig. 1. Solar receiver test bench.

2.1. Reflectance and transmittance measurement system

The optical characterization includes the spectral transmittance characterization of the glass envelope and the spectral reflectance of the inner absorber tube in the wavelength range of 300–2500 nm. As the transmission in the absorber is considered null, the measurement of the reflectance yields also the absorptance: 100%-reflectance. These measurements can be taken at any point on the PT receiver surface. The tube can be rotated ±180° and the optical measurement module can move along the tube by means of a 5 m length rail with resolution of 0.5 cm.

The schematic of the optical setup is depicted in Fig. 2. There are two main modules, the optical source module, fixed to the bench structure, and the optical measurement module moving along the receiver. The optical source module uses a xenon lamp as the light source and a monochromator to generate the optical signals in the wavelength range and an optical filter wheel to eliminate second harmonic interference. The light is also modulated by a chopper, with the aim of performing synchronous detection and avoids the contribution of ambient light. At the output of the monochromator, light is injected into two low-OH multimode fibers connected to the optical measurement module.

The optical measurement module includes two different optical sub-systems, one for the characterization of the spectral transmittance and the other for the reflectance. A transversal view of the transmittance measurement sub-system is shown in Fig. 2. A set of lenses first collimates and then focuses on the detectors the light from the fiber. By using a 10/90 wavelength independent optical beam splitter, a small part of the beam is used in a reference path to compensate optical source power fluctuations. The collimated beam passes through the glass envelope and the transmitted light is detected. Both silicon (300–1050 nm) and indium-gallium-arsenide (1050–2500 nm) PIN-photodiode detectors can be used at any time thanks to a 50/50 optical beam splitter.

A longitudinal view of the reflectance measurement sub-system is also shown in Fig. 2. The light out from the fiber is focused on the inner metal tube. The specularly reflected beam is then collected by a lens and focused a second time on the reflectance detectors. A reference path is also provided by a 10/90 beam splitter whereas Si and InGaAs detectors are again implemented using a 50/50 beam splitter.

The detected signals are digitalized by a data acquisition module and processed in a computer, using a lock-in algorithm, to obtain the transmission and reflection values for each wavelength.

The optical design provides the test bench with the capability of testing tubes of different diameters. The curvature of the outer an inner faces of the glass produces a lens effect which deviates the transmission beam trajectory. The trajectory of a single ray of the transmission beam incident at 45° and crossing the glass envelope is shown in Fig. 3. According to Snell's law, rays are refracted when passing through the glass. Rays deviation increases proportional to the incidence angle. As the incident beam has a significant diameter, each individual ray reaches the tube at a slightly different angle, resulting in an increased divergence on the transmitted beam. The lens effect causes changes in the diameter, position, direction and divergence of the light beam. These variations depend on the diameter of that tube.

In order to ensure a correct transmittance measurement independently of the glass enveloppe diameter, the incident beam diameter has been reduced to 5 mm to minimize its incidence angle range. The collecting lens diameter has been increased to assure that the beam is always captured as a whole. The detection module can be vertically displaced using micrometric stages to provide the correct position in each case.

Regarding the reflection measurement, the key point is that the vertical distance from the measurement module to the surface of